DEVELOPMENT AND VALIDATION OF SUSTAINABLE ORGANIC FILTERS: TECHNOLOGICAL INNOVATION FOR WATER TREATMENT IN VULNERABLE COMMUNITIES

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Abstract: Access to safe and potable water constitutes a fundamental human right and the basis for global public health; however, billions of people, especially in vulnerable communities in developing countries, still lack this essential resource. This article proposes the development and validation of an innovative, low-cost organic filter model, based on plant biomaterials, with an emphasis on applying Moringa oleifera seeds as a coagulant and adsorbent agent in decentralized purification systems, also known as Point-of-Use (POU) systems. The research aims to integrate technological, environmental, and social aspects, proposing a hybrid methodology that combines rigorous laboratory analyses for optimizing and validating filter efficiency with a detailed protocol for field studies, assessing the impact of adopting this technology in schools and low-income communities. The focus is on improving critical water potability indicators, including turbidity, apparent color, pH, and microbiological contamination (total coliforms and Escherichia coli), and the consequent potential reduction in the incidence of waterborne diseases, particularly acute diarrhea that disproportionately affects children under five years old. The proposed methodological approach includes the detailed physicochemical characterization of biomaterials, coagulation-flocculation tests (Jar Test), multi-stage filtration efficiency tests, and a Life Cycle Assessment (LCA) to holistically evaluate the environmental sustainability of the solution. It is expected to demonstrate, based on robust existing scientific literature and consolidated empirical evidence, that the use of biomaterials in sanitary engineering, exemplified by Moringa oleifera, constitutes a viable, scalable, low-environmental-impact, and socially impactful alternative for achieving Sustainable Development Goal 6 (SDG-6), promoting equitable access to

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potable water and basic sanitation in contexts of socioeconomic vulnerability and strengthening community resilience against the challenges posed by climate change and the degradation of water resources.

Keywords: Moringa oleifera, Water Treatment, Organic Filter, Natural Coagulant, Biomaterials, Vulnerable Communities, SDG-6, Environmental Health, Life Cycle Analysis, Decentralized Systems.

Introduction

Contextualization of the Global Water Crisis

Water is the driving force of all nature, as stated by Leonardo da Vinci, and an irreplaceable pillar for social, economic, and environmental development. However, the global water crisis, exacerbated by climate change, exponential population growth, unplanned urbanization, and increasing pollution of water bodies, represents one of the largest and most complex challenges of the 21st century. The United Nations (UN) estimates that more than 2 billion people worldwide lack access to safely managed drinking water services, and approximately 4.2 billion people lack safe sanitation services (NAÇÕES UNIDAS, [s.d.]). This scarcity is dramatically more pronounced in rural, peripheral, and low-income communities in developing countries, where the chronic lack of basic sanitation infrastructure and the consumption of contaminated water perpetuate a vicious cycle of poverty, disease, and underdevelopment.

The consequences for public health are devastating and well-documented. Waterborne diseases (WBDs), such as cholera, typhoid fever, bacillary dysentery, hepatitis A, giardiasis, and acute diarrheas of various etiologies, are responsible for millions of deaths annually, with a disproportionate and tragic impact on children under five years old, who represent the most vulnerable population. The World Health Organization (WHO) reports that diarrhea alone causes about 1.9 million infant deaths per year worldwide, making it one of the leading causes of mortality in this age group and an eloquent indicator of inequality in access to basic resources (ORGANIZAÇÃO MUNDIAL DA SAÚDE, 2023). This tragic scenario highlights a systemic and ethical failure in fulfilling a basic human right and constitutes a significant obstacle to the sustainable progress of developing nations.

Sustainable Development Goal 6 (SDG-6)

In response to this multifaceted crisis, the international community, through the United Nations 2030 Agenda, established Sustainable Development Goal 6 (SDG-6): "Ensure availability and sustainable management of water and sanitation for all" by 2030 (NAÇÕES UNIDAS, [s.d.]). This ambitious goal is not limited merely to physical access to water but encompasses dimensions of quality, safety, economic accessibility paradigm, moving away from exclusively centralized solutions, which have high capital and operating costs, and which often fail to effectively and efficiently serve dispersed, remote, and marginalized populations.

In this context, decentralized, or point-of-use (POU) water treatment technologies emerge as a strategic, complementary, and, in many cases, primary alternative. These technologies offer operational flexibility, low implementation and maintenance costs, adaptability to diverse local contexts, and, crucially, the possibility of community empowerment, technology transfer, and autonomy in water resource management (POOI; NG, 2018). POU systems treat water directly at the point of final consumption, whether in households, schools, health centers, or small communities, eliminating or drastically reducing the risk of recontamination during transport and storage, an endemic problem in many regions.

Biomaterials andMoringa oleiferaas a Sustainable Solution

Within the spectrum of POU solutions, the use of local, renewable, and sustainable biomaterials for water purification has gained scientific notoriety and increasing practical recognition in recent decades. Among these materials,Moringa oleifera, a fast-growing tree native to subtropical and tropical regions of Asia (mainly India) and widely cultivated in Africa, Latin America, and the Caribbean, stands out for its remarkable and multifunctional properties. Its seeds contain natural proteins with potent coagulant action, capable of agglutinating suspended particles, pathogenic microorganisms, and other pollutants, facilitating their subsequent removal through sedimentation or filtration processes (DESTA; BOTE, 2021; NDABIGENGESERE; NARASIAH; TALBOT, 1995). The use ofMoringa oleiferanot only represents an ecological, low-cost, and socially appropriate alternative to conventional chemical coagulants, such as aluminum sulfate (alum) and ferric chloride (which can be associated with human health problems and generate sludge that is difficult and costly to dispose of), but also aligns perfectly with a circular economy and sustainable development approach. It leverages a multifunctional plant resource (the leaves, pods, and roots of Moringa also have nutritional and medicinal uses) that is widely available in many of the regions most affected by drinking water scarcity, transforming a local challenge into an opportunity for innovation and development.

Objectives and Structure of the Article

This article proposes the development and rigorous validation of a sustainable organic filter that integratesMoringa oleifera seeds as the main active component in a multilayer filtration system. The central objective is to present a robust, replicable, and scalable technological model, whose effectiveness laboratory scale up to a comprehensive protocol for field validation, including social and environmental impact assessment. The research delves into the central hypothesis that a multilayer filtration system, utilizing low-cost local materials (sand, gravel, activated carbon from coconut shells) and Moringa oleifera as a coagulant, can consistently reduce water contamination indicators to levels safe for human consumption, as established by the WHO and national legislation, with high social acceptance, economic viability, and low environmental impact throughout its entire life cycle.

By connecting technological innovation in sanitary engineering with the pressing need for environmental health in vulnerable communities, and by adopting a holistic approach that integrates technical, social, economic, and environmental aspects, this work seeks to offer a significant theoretical and practical contribution to the advancement of SDG-6. It demonstrates a scalable, sustainable, and culturally appropriate path to bring safe water to those who need it most, contributing to the reduction of diseases, improvement of quality of life, and strengthening of community resilience.

Literature Review

The Water Crisis and the Need for Decentralized Solutions

Pressures on Water Resources

Accelerated urbanization, intensive industrialization, and unsustainable agricultural practices have pressured global water resources to an unprecedented level in human history. The contamination of rivers, lakes, aquifers, and water tables by untreated domestic effluents, toxic industrial discharges, and agricultural runoff loaded with pesticides and fertilizers severely compromises the quality of available water, making it unfit for human consumption without adequate prior treatment. In many regions of the world, particularly Sub-Saharan Africa, South Asia, and parts of Latin America, water treatment and distribution infrastructure is inadequate, obsolete, or simply nonexistent (POOI; NG, 2018).

Centralized water treatment and distribution systems, although highly effective in dense urban areas with adequate financial and technical resources, require high initial capital investment, elevated continuous operational costs (energy, chemicals, specialized labor), and complex and sophisticated technical management. These characteristics make them economically unviable and technically impractical for rural, remote, dispersed, or low-income communities, which are precisely those most in need of basic sanitation interventions (POOI; NG, 2018).

Waterborne Diseases and Impact on Public

Health This critical infrastructure gap creates a chronic dependence on unimproved or unprotected water sources, such as open wells, unprotected springs, rivers, and lakes, which are often contaminated with a wide range of pathogens, including bacteria (E. coli, Salmonella, Vibrio cholerae), viruses (rotavirus, norovirus, hepatitis A), and protozoa (Giardia lamblia, Cryptosporidium). The direct and inevitable consequence is the high prevalence of waterborne diseases (WBDs) in these populations. The WHO points out that the ingestion of contaminated water is one of the main vectors for the transmission of diseases such as cholera, typhoid fever, giardiasis, cryptosporidiosis, hepatitis A, and, above all, acute diarrheas of various etiologies (ORGANIZAÇÃO MUNDIAL DA SAÚDE, 2023). The impact is particularly severe in children under five years old, the elderly, and immunocompromised individuals, who constitute the population most vulnerable to severe infections and complications (SHAYO et al., 2023).

In addition to direct mortality, WBDs generate a substantial burden of morbidity, chronic malnutrition (due to recurrent episodes of diarrhea), impaired cognitive development in children, school and work absenteeism, and significant economic costs for families and already overburdened health systems. It is estimated that improving access to safe drinking water and sanitation could prevent at least 9.1

Moringa oleifera: A Promising Biocoagulant

Botanical Characteristics and Geographical Distribution

Moringa oleifera Lam. (Moringaceae family), popularly known as the “tree of life,” “miracle tree,” or “drumstick tree,” is a fast-growing, drought-resistant, multi-purpose tree, native to the Himalayan mountains in northwestern India. Currently, it is cultivated in tropical and subtropical regions worldwide, including Africa, Asia, Latin America, and the Caribbean, due to its adaptability to adverse climatic conditions and poor soils. Practically all parts of the plant (leaves, pods, seeds, flowers, roots, bark) have traditional uses in food, medicine, and agriculture, making it a species of great socioeconomic and nutritional value for rural communities (NDABIGENGESERE; NARASIAH; TALBOT, 1995).

Coagulation Mechanism

The search for effective, low-cost, environmentally benign, and socially appropriate coagulants has led, in recent decades, to in-depth scientific investigation of plant-based materials. Among these, Moringa oleifera has emerged as one of the most promising and well-studied alternatives to conventional metallic salts, such as aluminum sulfate (alum) and ferric chloride. Moringa oleifera seeds contain a water-soluble cationic protein that acts as a potent natural coagulating agent (NDABIGENGESERE; NARASIAH; TALBOT, 1995).

The coagulation mechanism of Moringa oleifera was elucidated in seminal and widely cited studies, such as that by Ndabigengesere et al. (1995). The authors demonstrated, through electrophoresis and chromatography techniques, that the active agents are dimeric proteins with a molecular weight of around 13 kDa and a high isoelectric point, between 10 and 11, which gives them a

Efficiency in the Removal of Turbidity and Microorganisms

The efficiency of Moringa oleifera in removing turbidity and pathogenic microorganisms is comparable, and in some cases superior, to that of aluminum sulfate, depending on the characteristics of the raw water (pH, alkalinity, type, and concentration of particles). Experimental studies demonstrate turbidity removals above 90-99% in waters with different levels of initial contamination, ranging from 50 to 500 NTU (Nephelometric Turbidity Units) (DESTA; BOTE, 2021; PATERNIANI et al., 2009). In addition to its primary coagulant function, Moringa oleifera seed extracts exhibit direct antimicrobial activity, contributing to water disinfection. In vitro studies have demonstrated bactericidal and bacteriostatic activity against a variety of pathogenic bacteria, including E. coli, Salmonella spp., and Staphylococcus aureus (NZEYIMANA et al., 2024). This dual function (coagulant and antimicrobial) makes it particularly attractive for simplified and multi-barrier treatment systems.

Comparative Advantages over Chemical Coagulants

The advantages of using Moringa oleifera over conventional chemical coagulants are multiple, significant, and encompass environmental, economic, social, and public health dimensions. From the perspective of origin and sustainability, while aluminum sulfate is a mineral and synthetic product, dependent on energy-intensive industrial processes (bauxite mining, refining, chemical production) and globalized supply chains, Moringa oleifera seeds are of plant origin, renewable, and can be cultivated locally in tropical and subtropical regions, precisely where the need for water treatment solutions is most pressing. This drastically reduces the carbon footprint associated with transport and industrial production (DESTA; BOTE, 2021; NDABIGENGESERE; NARASIAH; TALBOT, 1995).

In terms of toxicity and human health, residual aluminum present in water treated with aluminum sulfate has been a subject of scientific and public health concern. Epidemiological and toxicological studies suggest a possible association between chronic aluminum exposure and risks of neurotoxicity, as well as sodium carbonate), which increases operational complexity and costs. Furthermore, alum consumes the natural alkalinity of the water, which can be problematic in waters with low alkalinity. In contrast, Moringa oleifera has a minimal effect on pH and a negligible impact on alkalinity, considerably simplifying the treatment process and making it more robust and less dependent on chemical adjustments (DESTA; BOTE, 2021; NDABIGENGESERE; NARASIAH; TALBOT, 1995).

The issue of generated sludge is particularly relevant from an environmental and operational perspective. Aluminum sulfate produces a considerable volume of chemical sludge, rich in aluminum hydroxide, which is difficult to dewater, costly to dispose of, and potentially hazardous to the environment if not managed properly. In many developing countries, the inadequate management of this sludge represents a significant environmental problem. In contrast, Moringa oleifera generates a significantly smaller volume of sludge, estimated at about four to five times less, and is organic in nature, thus biodegradable, easier to handle, and has the potential for use as fertilizer or soil conditioner (DESTA; BOTE, 2021; NDABIGENGESERE; NARASIAH; TALBOT, 1995).

From an economic standpoint, the cost of aluminum sulfate is high

The upper layer, composed of materials with larger particle size (coarse gravel), acts as pre-filtration, removing larger debris, leaves, and coarse particles, and distributing the water flow more uniformly over the lower layers. The intermediate layers, made of coarse sand and fine sand, are responsible for removing most suspended particles, flocs, protozoan cysts (Giardia, Cryptosporidium), and a significant portion of bacteria. The fine sand layer, in particular, is crucial for filtration efficiency because, in addition to physical removal, an active biological layer (biofilm or “schmutzdecke”) develops on its surface, composed of beneficial microorganisms that contribute to the degradation of organic matter and the removal of pathogens (MINTZ et al., 2001).

Adsorption and Adsorbent Biomaterials

The innovation lies in the incorporation of other biomaterials with specific adsorbent properties to remove dissolved contaminants that are not effectively eliminated solely by coagulation and physical filtration. Adsorption is a surface process where ions, molecules, or atoms of a substance (adsorbate) adhere to the surface of a porous material (adsorbent) through physical forces (physical adsorption or physisorption, such as Van der Waals forces) or chemical bonds (chemical adsorption or chemisorption). Biomaterials such as activated carbon from coconut shells, carbonized sugarcane bagasse, modified sawdust, rice husks, and natural or modified clays have demonstrated a high capacity to adsorb heavy metals (lead, cadmium, mercury, arsenic), pesticides, dissolved organic compounds, dyes, and odors (KUMAR et al., 2024; YADAV et al., 2021).

Granular activated carbon (GAC), produced from coconut shells, is particularly effective due to its high specific surface area (typically 8)

Importance of Community Participation and Social Acceptance

The successful and sustainable implementation of any water treatment technology in vulnerable communities depends not only on its technical efficacy proven in the laboratory, but also, and crucially, on its social acceptance, long-term economic viability, ease of operation and maintenance using local resources, and environmental sustainability throughout its entire life cycle. Case studies on the implementation of filters and other POU technologies in schools, homes, and small communities in various countries consistently highlight the fundamental importance of a participatory approach, which actively involves the community from the initial phases of design and planning, through construction and installation, to the operation, maintenance, and monitoring of the systems (FREEMAN; CLASEN, 2011; NELSON et al., 2021).

Community participation is not merely a matter of courtesy or “consultation,” but an essential element for ensuring technology ownership, the building of local capacity, the adaptation of the design to the specific needs and conditions of the community, and long-term sustainability. When communities are merely passive recipients of externally imposed technologies, without understanding how they work or without a sense of ownership, abandonment and failure rates are dramatically high (NELSON et al., 2021).

Schools, in particular, function as strategic centers for the dissemination of knowledge, hygiene practices, and healthy behaviors, where children can act as agents of change in their families and communities, taking home the lessons learned about the importance of safe water, hand hygiene, and sanitation (SOUZA et al., 2021). Interventions in schools have been shown not only to improve health and reduce student absenteeism but also to have a multiplier effect on household practices (FREEMAN; CLASEN, 2011).

Life Cycle Assessment (LCA) and Environmental Sustainability

To holistically and rigorously assess the sustainability of water treatment interventions, Life Cycle Assessment (LCA) is a powerful and widely recognized methodological tool. LCA is a standardized technique (ISO 14040 and ISO 14044) that allows for the quantification of the environmental impacts of a product, process, or service from raw material extraction, through production, transport, use, to final disposal or recycling, in an approach known as “cradle-to-grave” (RASHID et al., 2023).

The application of LCA to decentralized water treatment systems based on biomaterials, such as the filter proposed in this study, tends to reveal a significantly smaller environmental footprint compared to centralized systems that use energy- and resource-intensive chemicals. The local production of Moringa oleifera,

Sand, gravel, and coconut shell activated carbon, for example, drastically reduce the impacts associated with long-distance transport and the industrial production of chemical coagulants, which involve mining, high-temperature chemical processes, and energy consumption (GARRIDO-BASERBA et al., 2024; RASHID et al., 2023).

Recent Life Cycle Assessment (LCA) studies applied to decentralized water treatment systems demonstrate that these systems can have superior environmental performance in impact categories such

Proposed Methodology

To meet the central objective of rigorously and comprehensively developing and validating a sustainable organic filter, a multiphase and integrated research methodology is proposed, combining experimental laboratory approaches with protocols for field studies and social and environmental impact assessment. This methodology was designed to be replicable, robust, and scientifically sound, allowing not only for the assessment of the filter's technical efficacy under controlled conditions but also its viability, acceptance, and sustainability in real-world usage contexts.

Filter Prototype Development and Construction

Multilayer Filtration System Design

The filter design will be based on a downward-flow multilayer filtration system, utilizing low-cost materials that are locally available and easily acquired in many vulnerable communities. The prototype will be constructed using food-grade cylindrical containers (e.g., High-Density Polyethylene - HDPE - plastic buckets with a 20-liter capacity), which are widely available, durable, lightweight, and low-cost. The system will follow a gravitational flow model, requiring no electrical energy or pumping, which is a crucial advantage for contexts of energy scarcity.

The internal structure of the filter will be composed of the following layers, arranged from top to bottom:

Layer 1 - Coarse Pre-filtration (Coarse Gravel): The top layer will consist of coarse gravel, with an approximate particle size of 1 to 2 cm and a thickness of about 5 to 7 cm. This layer functions to remove larger debris (leaves, twigs, insects), protect the lower layers from premature clogging, and distribute the water flow more uniformly over the filter surface.

Layer 2 - Fine Pre-filtration (Fine Gravel): Below the first layer, a layer of fine gravel, with an approximate particle size of 0.5 to 1 cm and a thickness of 5 to 7 cm, will continue the pre-filtration process, removing intermediate-sized particles.

Layer 3 - Primary Filtration (Coarse Sand): A layer of coarse sand, with an approximate particle size of 0.5 to 1 mm and a thickness of 10 to 15 cm, will act to remove suspended particles, protozoa (Giardia, Cryptosporidium), a significant portion of bacteria, and the development of an active biofilm that contributes to biological purification.

Layer 4 - Adsorption (Granular Activated Carbon - GAC): This layer will be composed of granular activated carbon (GAC) produced from coconut shells, with an approximate particle size (granulometry) of 1 to 3 mm and a thickness of 10 to 15 cm. GAC is chosen for its high surface area, capacity to adsorb dissolved organic compounds, residual chlorine (if applicable), some heavy metals, pesticides, and substances that impart unpleasant taste and odor to the water, significantly improving the effluent’s organoleptic characteristics.

Layer 5 - Support and Drainage (Fine and Coarse Gravel): A final layer of fine gravel (5 cm) followed by coarse gravel (5 cm) at the base of the filter will prevent clogging of the water outlet, provide structural support to the upper layers, and facilitate the uniform drainage of the treated effluent.

Between each layer of filtering material, fine nylon screens (mesh size of approximately 1 mm) will be used to prevent the mixing of materials with different particle sizes and maintain the structural integrity of the filter bed. The treated water outlet will be positioned at the base of the container, equipped with a tap or valve for flow control.

Preparation and Pre-treatment of Filtering Materials

All filtering materials (gravel, sand, activated carbon) will undergo a rigorous preparation and pre-treatment process before the filter assembly, to ensure their cleanliness, particle size uniformity, and filtering efficiency. Gravel and Sand: They will be thoroughly washed with running water to remove dust, the coagulant solution will be prepared from high-quality, mature Moringa oleifera seeds, preferably collected from healthy trees grown without the use of pesticides.

- Hulling/Shelling: The seeds will be manually hulled/shelled to obtain the internal kernels, which contain the highest concentration of coagulant proteins. The outer shell, although it also contains some proteins, is less effective and may introduce impurities.
- Drying: The hulled kernels will be dried in an oven at a mild and controlled temperature (approximately 50 °C) for a period of 24 to 48 hours, or until they reach a moisture content below 10%. Drying is important to facilitate grinding, increase the shelf life of the material, and standardize the protein concentration. Very high temperatures must be avoided so as not to denature the active proteins.
- Grinding: Next, the dried kernels will be crushed in a mill (hammer mill, ball mill, or industrial blender) until a fine and homogeneous powder is obtained, with a particle size smaller than 0.5 mm. The powder will be stored in airtight containers, protected from light and moisture, until the time of use.

Extraction of the Coagulant Protein

The Moringa seed powder will be mixed with a saline solution to extract the active cationic proteins. Studies show that extraction with a saline solution (e.g., 1M NaCl) is more efficient than extraction with distilled water alone, as it increases the solubility and stability of the proteins (NDABIGENGESERE; NARASIAH; TALBOT, 1995).

- Ratio: The typical ratio is 1 g of seed powder to 100 mL of saline solution (1M NaCl), but this ratio can be adjusted based on preliminary tests and the characteristics of the water to be treated. about contaminant removal.

Preparation of Synthetic Water

Synthetic waters with different levels of turbidity and microbiological contamination will be prepared to simulate surface waters (rivers, lakes, shallow wells) found in rural communities and to evaluate the robustness of the treatment system.

- Turbidity: Turbidity will be induced by adding standard clay (bentonite or kaolinite) in varied concentrations to obtain turbidity levels of 50, 100, 200, and 300 NTU (Nephelometric Turbidity Units), covering a representative range of surface waters.
- Organic Matter: Natural organic matter (humus, leaf extract) will be added to simulate the presence of humic and fulvic substances, which are common in surface waters and can interfere with coagulation and disinfection.
- Microbiological Contamination: The synthetic water will be inoculated with a non-pathogenic strain ofEscherichia coli(e.g., ATCC 25922) at known concentrations (e.g., 10^3 to 10^5 CFU/100 mL) to evaluate the system's bacterial removal efficiency. The use of a non-pathogenic strain ensures the safety of the researchers and avoids the need for high-level biosafety facilities.

Coagulation Tests (Jar Test)

Bench-scale coagulation tests (Jar Test) will be performed to determine the optimal dosage of theMoringa oleiferasolution for each turbidity level of the synthetic water. The Jar Test is a standardized procedure widely used in sanitary engineering to optimize coagulation-flocculation processes. Procedure: Six 1-liter beakers, containing samples of the synthetic water, will be placed in a Jar Test apparatus. Different concentrations of theMoringa coagulant solution (e.g., 0

Using the optimal coagulant dosage defined in the Jar Test, the synthetic water will be pre-treated with the Moringa coagulant, and after an adequate sedimentation time (30-60 minutes), the supernatant will be passed through the prototype of the multilayer filter.

Samples will be collected before treatment (raw water), after coagulation-sedimentation (settled water), and after filtration (filtered water) for analysis of the following parameters, following the standardized methods described in the Standard Methods for the Examination of Water and Wastewater (APHA; AWWA; WEF, 2017):

Physicochemical Parameters:

- Turbidity: Measured in a turbidimeter (nephelometric method), expressed in NTU.
- Apparent Color: Measured in a spectrophotometer (spectrophotometric method), expressed in Hazen units (uH) or Pt-Co.
- pH: Measured in a pH meter (potentiometric method).
- Electrical Conductivity: Measured in a conductivity meter, expressed in µS/cm.
- Total Dissolved Solids (TDS): Calculated from conductivity or measured gravimetrically.

Microbiological Parameters:

- Total Coliform and E. coli Count: Using the membrane filter method (filtration on a 0.45 µm membrane, incubation in specific culture medium, colony counting) or the Colilert® method (defined enzymatic substrate, colorimetric/fluorimetric reading), expressed in CFU/100 mL or MPN/100 mL (Most Probable Number).

Specific Chemical Contaminants (optional, depending on the water source):

- Heavy Metals: Analysis of lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg) by atomic absorption spectrometry (AAS) or inductively coupled plasma optical emission spectrometry (ICP-OES), expressed in mg/L or µg/L.

- Nitrates and Nitrites: Analysis by colorimetric methods or ion chromatography, expressed in mg/L. The results will be compared with the WHO drinking water standards (ORGANIZAÇÃO MUNDIAL DA SAÚDE, 2023) and Ordinance GM/MS Nº 888/2021 of the Brazilian Ministry of Health (BRASIL, 2021) to evaluate the compliance of the treated water.

Protocol for Field Study and Social Impact Assessment

Following successful laboratory validation, a detailed protocol is proposed for the implementation and evaluation of the filter in a real-world context, aiming to assess its feasibility, acceptance, effective use, and impact on the health and quality of life of a target community.

Community Selection and Baseline Study Community selection will be based on criteria of water vulnerability (lack of access to potable water, dependence on unimproved sources), the presence of a partner community organization (residents' association, school, health post) willing to collaborate, and logistical feasibility for access and monitoring.

A baseline study will be conducted before the implementation of the filters to collect quantitative and qualitative data on:

- Water Sources and Treatment Practices: Household survey to identify the water sources used (well, river, lake, cistern), current treatment practices (boiling, chlorination, filtration, none), and water storage.
- Perception of Water Quality: Semi-structured interviews and focus groups to assess the community's perception of water quality (taste, odor, appearance, safety) and the willingness to adopt new treatment technologies.
- Incidence of Diarrheal Diseases: Collection of retrospective data on the incidence of diarrheal diseases over the last 6 to 12 months, based on records from local health posts

and household surveys (2-week recall).

- Water Quality Analysis of Local Sources: Collection and analysis of water samples from the main sources used by the community (wells, rivers, cisterns) for the same physical-chemical and microbiological parameters described in section 3.3.3, establishing the baseline water quality before the intervention.

Participatory Implementation and Community Training

The construction and installation of the filters will be carried out in participatory workshops with community members, local school students, and teachers. The training will cover the following in a practical and didactic manner:

- Filter Operating Principles: Simplified explanation of how Moringa coagulation and multi-layer filtration work, using visual materials and practical demonstrations.
- Filter Construction: Active participation in assembling the filters, from material preparation to layer arrangement and tap installation.

Preparation of the Moringa Coagulant: Practical training on

- Maintenance and Cleaning: Training on periodic filter cleaning (removal of the top layer of sand when there is a significant reduction in flow rate), replacement of activated carbon layers (every 6-12 months, depending on the volume treated), and general care.
- Hygiene and Safe Storage: Reinforcement of hand hygiene practices, cleaning of water storage containers, and prevention of recontamination.

Illustrated educational materials (booklets, posters) will be developed and distributed in accessible and culturally appropriate language.

Monitoring and Impact Assessment

Over a period of 6 to 12 months, continuous and systematic monitoring will be carried out to evaluate the effective use, efficacy, and impact of the filters:

- Water Quality: Monthly collection of treated water samples from filters in households and the school for analysis of the same baseline physicochemical and microbiological parameters. Comparison with untreated water samples (control) and with potability standards. Health: Monitoring the incidence of diarrheal diseases through records from local health posts and biweekly or monthly household surveys, comparing with baseline data and, if possible, with a control community (without intervention).
- Use and Acceptance: Periodic semi-structured interviews and focus groups to evaluate users' perception of the filter (ease of use, water taste, appearance, confidence in safety), frequency of use, challenges encountered (difficulty obtaining Moringa seeds, preparation time, maintenance), and suggestions for improvements.
- Sustainability: Assessment of the community's capacity to maintain the filters functioning long-term, including the local availability of replacement materials (Moringa seeds, activated carbon) and community organization for collective management.

Environmental Sustainability Analysis (LCA)

A simplified, but rigorous, Life Cycle Assessment (LCA) will be conducted to compare the environmental impact of the Moringa filter with two alternatives commonly used in low-income communities: (a) conventional treatment with aluminum sulfate (in small-scale systems) and (b) consumption of boiled water. The analysis will follow the guidelines of ISO 14040 and ISO 14044 standards, focusing on the following life cycle phases: Extraction and Processing of Raw Materials:

- Moringa Filter: Cultivation and harvesting of Moringa (use of land, water, fertilizers, if applicable), extraction of sand and gravel (small-scale mining, local transport), production of coconut shell activated carbon (coconut shell collection, carbonization, activation).
- Alum Treatment: Bauxite mining, refining for alumina production, production of aluminum sulfate (energy-intensive chemical processes).
- Boiling: Consumption of liquefied petroleum gas (LPG), natural gas, firewood, or electricity (depending on the local energy source).
- Transport: Transportation of materials from the production/extraction site to the community (distances, mode of transport).
- Use: Filter operation (does not consume energy), operation of the alum treatment system (energy consumption for mixing, if applicable), boiling (continuous energy consumption). End-of-Life: Disposal of filter materials (sand, gravel, activated carbon – all biodegradable or inert), disposal of aluminum sludge (potentially hazardous), combustion gas emissions (boiling).

The impact assessment will focus on categories relevant to the context of developing countries:

Global Warming Potential (GWP): Emissions of greenhouse gases (CO_2 , CH_4 , N_2O), expressed in kg CO_2 equivalent.

- Eutrophication: Emissions of nutrients (nitrates, phosphates) into water bodies.
- Human Toxicity: Exposure to toxic substances (residual aluminum, combustion

emissions).

- Non-Renewable Resource Use: Consumption of fossil fuels, minerals.

The LCA is expected to demonstrate the environmental superiority of the proposed solution, reinforcing its alignment with the principles of sustainable engineering and the circular economy (GARRIDO-BASERBA et al., 2024; RASHID et al., 2023).

Expected Results and Discussion

Based on the proposed methodology and the vast existing scientific literature on the efficacy ofMoringa oleiferaand multi-layer filtration systems, the expected results of this study are the following:

High Contaminant Removal Efficiency

The synergistic combination of coagulation-flocculation using Moringa oleifera and multilayer filtration is expected to achieve a turbidity removal efficiency greater than 95%, reducing initial turbidity from 50-300 NTU to values below 5 NTU, and ideally below 1 NTU, meeting WHO standards and Ministerial Ordinance GM/MS No. 888/2021 (BRASIL, 2021; PATERNIANI et al., 2009). Apparent color removal should also be significant, exceeding 80-90%, thereby improving the aesthetic characteristics of the water.

Regarding microbiological removal, a 2 to 3 log reduction (99% to 99.9%) of E. coli is expected, meaning a reduction from initial concentrations of 10^3-10^5 CFU/100 mL to values below 10^1 CFU/100 mL, bringing the treated water within potability standards for human consumption (CLASEN et al., 2015; PATERNIANI et al., 2009). The combination of the coagulant and antimicrobial action of Moringa with physical and biological filtration (biofilm in the fine sand layer) is the mechanism responsible for this high efficiency.

Positive Impact on Community Health

The provision of safe and quality water for human consumption should lead to a statistically significant reduction in the incidence of diarrheal diseases in the target community, compared to the baseline (pre-intervention period) and, ideally, compared to a control group (similar community without intervention). Intervention studies involving water community demonstrates the capacity to keep the filters operational using local resources (cultivation or acquisition of Moringa seeds, replacement of activated carbon).

Proven Environmental Sustainability

The Life Cycle Assessment (LCA) must quantify and unequivocally demonstrate the environmental advantages of the proposed organic filter. The Moringa filter is expected to show a significantly lower carbon footprint (Global Warming Potential) compared to treatment with aluminum sulfate and, especially, compared to boiling water.

Boiling, although effective for disinfection, consumes large amounts of energy (firewood, LPG, electricity), resulting in substantial emissions of CO_2 and other greenhouse gases. In regions where firewood is the main energy source for boiling, this contributes to deforestation and environmental degradation. Since the Moringa filter does not consume energy during operation and uses materials with low environmental impact, it should have a much lower carbon footprint.

The comparison with alum treatment should highlight the elimination of hazardous chemical sludge generation and the reduction of impacts associated with bauxite mining and the industrial production of aluminum sulfate. The use of biodegradable and renewable biomaterials reinforces the sustainability of the solution.

Scalable and Replicable Model

The proposed filter methodology and design constitute a model that can be easily adapted and replicated in different geographical, cultural, and socioeconomic contexts, with adjustments to locally available materials (for example, replacing coconut shell charcoal with bamboo charcoal or other local biomass). The simplicity of the system, the use of low-cost and locally available materials, and the ease of technology transfer and local capacity building promote community autonomy in managing their own water resources and facilitate the scalability of the solution.

This integrated approach, which connects rigorous laboratory validation with real-world impact assessment, and which holistically considers technical, social, economic, and environmental aspects, is crucial for the success and sustainability of environmental health interventions. Many water treatment technologies fail not due to intrinsic technical deficiencies, but because they do not adequately consider the social, cultural, economic, and environmental factors that govern their long-term adoption, use, and maintenance. By placing community participation, sustainability, and equity at the center of the project, this study not only validates a filter but proposes a model of environmental health intervention that can contribute significantly to the achievement of SDG-6.

Conclusion

This article has outlined a comprehensive, rigorous, and scientifically sound framework for the development and validation of an organic and sustainable water filter, centered on the use ofMoringa oleifera as a natural and effective bio-coagulant. The proposed research represents a critical and innovative fusion of sanitary engineering, environmental health, social sciences, and sustainability, addressing one of the most persistent, complex, and urgent challenges of our time: universal access to safe drinking water, especially for the planet's most vulnerable and marginalized populations.

The detailed methodology presented, which ranges from rigorous laboratory optimization, through a comprehensive protocol for participatory community implementation, to a life cycle analysis for assessing environmental sustainability, establishes a clear, replicable, and robust roadmap for creating a solution that is not only technically effective and scientifically validated, but also socially appropriate, culturally sensitive, economically viable, and environmentally responsible.

The strength and differentiation of the proposed approach lie in its strategic reliance on local, renewable, and low-cost resources, which intrinsically increases the likelihood of community ownership, management autonomy, and long-term sustainability. By replacing conventional chemical coagulants—which are expensive, dependent on globalized supply chains, and potentially hazardous—with a multifunctional, renewable biomaterial widely available in tropical and subtropical regions, the proposed technology minimizes negative environmental impacts, promotes a circular economy at the local level, and generates opportunities for socioeconomic development for rural communities.

Field validation, with an explicit focus on active community participation, health and hygiene education, and local capacity building, ensures that the intervention is culturally sensitive, socially accepted, and that its benefits—notably the significant reduction of waterborne diseases, the improvement of quality of life, and the strengthening of community resilience—are maximized, long-lasting, and equitably distributed.

In summary, the organic filter model utilizing Moringa oleifera transcends mere technical water purification. It presents itself as a powerful and multifaceted tool for sustainable development, capable of generating cascading positive impacts on public health, education, gender equity (by reducing the time women and girls spend collecting water), economic resilience, and environmental sustainability of vulnerable populations. The research, implementation, and dissemination of such social technologies are concrete, essential, and urgent steps to transform the ideal of Sustainable Development Goal 6 into a tangible and measurable reality for all, ensuring that water is, in fact, a source of life, health, and well-being, and not of disease, inequality, and suffering.

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